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Realistic Subscale Evaluations of the Mechanical Properties of Advanced Disk Superalloys

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REALISTIC SUBSCALE EVALUATIONS OF THE MECHANICAL PROPERTIES OF ADVANCED DISK SUPERALLOYS

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Abstract

A series of experimental powder metallurgy disk alloys were evaluated for their processing characteristics and high temperature mechanical properties. Powder of each alloy was hot compacted, extruded, and isothermally forged into subscale disks. Disks were subsolvus and supersolvus heat treated, then quenched using procedures designed to reproduce the cooling paths expected in large-scale disks. Mechanical tests were then performed at 538, 704, and 815 °C. Several alloys had superior tensile and creep properties at 704 °C and higher temperatures, but were difficult to process and prone to quench cracking, chiefly due to their high gamma prime solvus temperature. Several other alloys had more favorable processing characteristics due to their lower gamma prime solvus temperature and balanced time-dependent properties at 704 °C. Results indicate an experimental low solvus, high refractory alloy can build upon the best attributes of all these alloys, giving exceptional tensile and creep properties at high temperatures with good processing characteristics due to a low gamma prime solvus.

Introduction

Advanced powder metallurgy disk alloys such as ME3 and Alloy 10 were designed using divergent screening and optimization approaches for composition and processing variables in several cooperative government-industry programs. ME3 was developed and scaled-up by the team of NASA, General Electric, and Pratt & Whitney in the NASA High Speed Research/Enabling Propulsion Materials (HSR/EPM) Compressor/Turbine Disk program to have extended durability at 650 °C in large engine compressor and turbine disks [1]. Alloy 10 was developed by Honeywell Engine Systems to produce superior tensile, creep, and fatigue resistance in smaller engine disks at temperatures above 650 °C [2].

There is a long-term need for disks with higher rim temperature capabilities of 704 °C or more. This would allow higher compressor exit (T3) temperatures and allow the full utilization of advanced combustor and airfoil concepts under development. The balance of mechanical properties necessary to achieve these temperature capabilities could vary with engine size and engine cycle design, as well as the particulars of a selected potential disk design and location in an engine. Such detailed design assessments are beyond the scope of this study. However, a brief screening characterization of the mechanical properties of experimental disk alloys at high temperature would allow initial assessments of the balance of properties produced by modified chemistries.

Variations in disk alloy chemistry can be used to help achieve these improvements in temperature capability. This can be assessed by processing and testing subscale disks made with intentionally varied experimental disk alloy powder chemistries. However, a very important consideration in heat treating subscale disks is the quenching procedures after solution heat treatments. Small subscale disks having low mass tend to cool much faster than large-scale disks for a given quenching procedure. This can produce unrealistic mechanical properties in the subscale material, which cannot be easily attained in large scale disks. Therefore, modified quenching procedures are necessary for subscale disks.

The objective of this study was to develop and perform realistic quenching heat treatments on subscale disks of several advanced powder metallurgy disk superalloys. The realistic quenching heat treatments were first developed and verified to give in subscale disks comparable mechanical properties to large scale disks. The high temperature mechanical properties of experimental superalloys were then screened in search of an alloy having high temperature capability.

Materials and Procedure

A series of experimental advanced powder metallurgy disk alloys were evaluated for their processing characteristics and high temperature mechanical properties. The overall variations of composition in weight percent among these alloys were 3.3-4.0 Al, 0.024-.030 B, 0.028-.050 C, 15.2-20.7 Co, 9.5-13.3 Cr, 2.5-3.7 Mo, 0-1.9 Nb, 1.0-2.6 Ta, 3.3-3.8 Ti, 2.1-5.9 W, 0.05-0.1 Zr, and balance Ni. Powder of each superalloy was hot compacted and extruded. Extrusion segments of the superalloys were machined to mults 7 to 8 cm dia. and 15 to 16 cm long, then forged into subscale disks about 13 to 14 cm in diameter and 4 cm thick by Wyman-Gordon Forgings. They were then heat treated using several procedures.

Mechanical test conditions of subscale disks after heat treatments were selected to screen high temperature properties and allow limited direct comparisons with specimen tests from the scale-up disks.

Tensile Tests

Tests of subscale material were performed at Dickson Testing Company and NASA GRC on specimens machined by Metcut Research Associates having a gage diameter of 0.41 cm and gage length of 2.5 cm in a uniaxial test machine employing a resistance heating furnace and axial extensometer according to ASTM E21.

Creep Tests

Machining of subscale disk creep specimens was performed by Metcut Research Associates. Specimens having a gage diameter of 0.64 cm and gage length of 3.8 cm were machined and tested in uniaxial lever arm constant load creep frames using resistance heating furnaces and shoulder-mounted extensometers. The creep tests were performed by NASA GRC and Metcut Research Associates according to ASTM E139.

Fatigue Crack Growth Tests

Machining of surface flaw fatigue crack growth specimens from subscale disks was performed by BITEC CNC Machining. All specimens had a rectangular gage section 1 cm wide and

0.46 cm thick, with a surface flaw about 0.036 cm wide and 0.018 cm deep produced by electro-discharge machining. The fatigue crack growth specimens were then tested at NASA GRC. Tests were performed in a closed-loop servohydraulic test machine using resistance heating and potential drop measurement of crack growth. Pre-cracking was performed at room temperature. Tests were then performed at elevated temperatures using a maximum stress of 690 MPa. Cyclic dwell tests were performed at 704 °C with a 90 s dwell at maximum stress, using a stress ratio of 0.05.

Grain sizes were determined according to ASTM E112 linear intercept procedures using circular grid overlays.

Results and Discussion

Heat Treatments and Microstructure Response

Grain size as a function of solution heat treatment temperature was first screened for all alloys using small coupons. Grain size increased nonlinearly with temperature as shown in Fig. 1. At low solution temperatures the grain size was relatively stable at ASTM 12-11 (5 to 10 μm). Increasing temperature to a certain level produced a sharp step increase in grain size to ASTM 7-6 (40 to 55 μm). This was due to the dissolving of most of the prior existing coarse "primary" γ′ precipitates which constrain grain growth. The temperature producing a transitioning grain size of ASTM 9.5 (13 μm) within the step increase was selected to define a practical "solvus" temperature of the alloy which dissolved enough of the "primary" γ′ precipitates (90 to 95 percent) to allow the grain growth. The solvus temperature producing this sharp increase in grain size varied among the alloys. ME3 and a group of experimental "LS" series alloys had low solvus temperatures of 1150 to 1160 °C. Alloy 10 and a group of experimental "HS" series alloys had high solvus temperatures of 1170 to 1190 °C.

It was intended that the subscale disks be quenched from the solution heat treatments at cooling rates typically expected at near-surface to deeply imbedded locations of large scale disks of one to several hundred pounds weight which were oil quenched. Due to the much lower weight and volume of the subscale disks, this required design and screening of slower cooling procedures than typically employed for large disks. A procedure of fan air cooling starting 2 minutes after

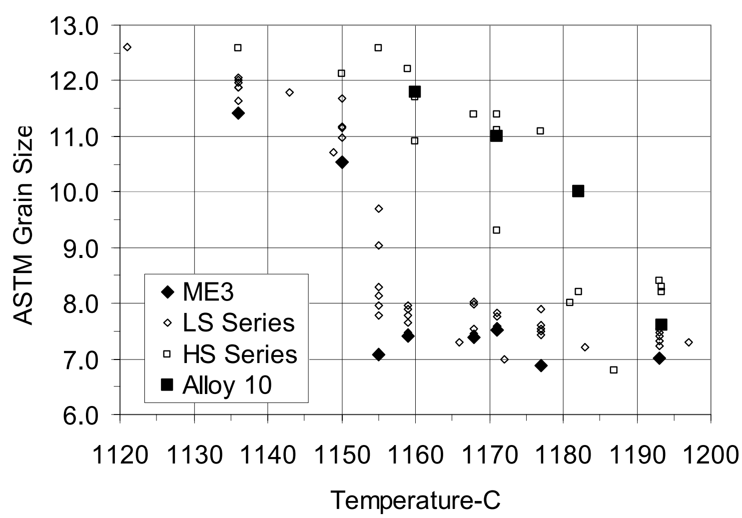


Figure 1: Grain size versus solution heat treatment temperature.

removal from the furnace was adopted to simulate deeply imbedded bore locations in large disks. An additional disk of each alloy was directly oil quenched starting 30 seconds after removal from the furnace, to simulate faster cooling rates near the surfaces of large disks. The cooling temperature-time data of thermocouples embedded in the middle ("bore") and near the corner ("rim") of a subscale disk are compared in Fig. 2. The temperature-time paths of cooling measured in the subscale disks was similar to that expected for large disks. The thermocouple temperature-time data recorded from 4 thermocouples embedded in one of the subscale disks during fan air and oil quenching cycles was analyzed using a commercial heat transfer computer code in order to assign approximate cooling rates, averaged over the temperature range of solution temperature to 815 °C, for each specimen. All subscale disks were subsequently given an aging heat treatment of 815 °C/8h.

The response to quenching varied among the alloys. All disks survived quenching from subsolvus solution temperatures. However, several of the disks formed edge cracks of 1 to 8 cm length during quenching from supersolvus solution temperatures. The location and intergranular mode of these quench cracks was comparable to that previously observed in large scale disks, Fig. 3. Comparing among alloys, alloys having the high solvus temperatures and corresponding supersolvus solution heat treatment temperatures had a propensity of cracking. This has also been observed in preliminary repeated testing of tensile and coin-sized disk specimens of Alloy 10 and ME3, respectively [3, 4]. Therefore, it will be important to consider solvus temperature when comparing the resulting mechanical properties among the alloys.

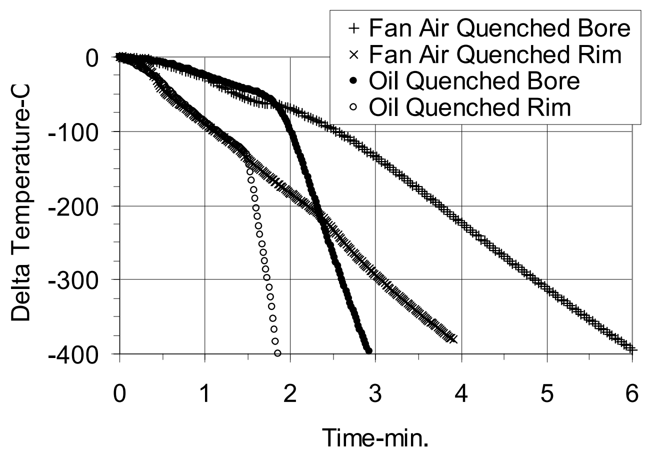
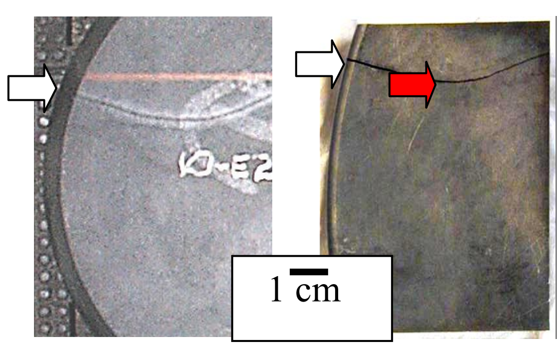
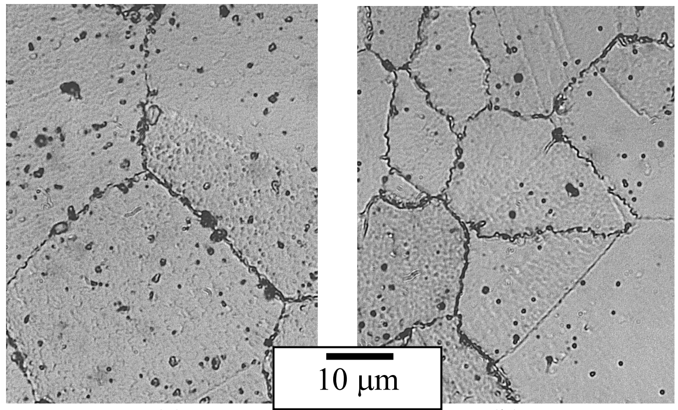


Figure 2: Thermocouple temperature versus time at different locations in subscale disks.



(a) (b)

Figure 3: Quench cracks in high solvus alloy disks: (a) Subscale disk (b) Large scale disk.



(a) (b)

Figure 4: Typical microstructures: (a) Supersolvus solution heat treated, then oil quenched (b) Supersolvus solution heat treated, fan air cooled.

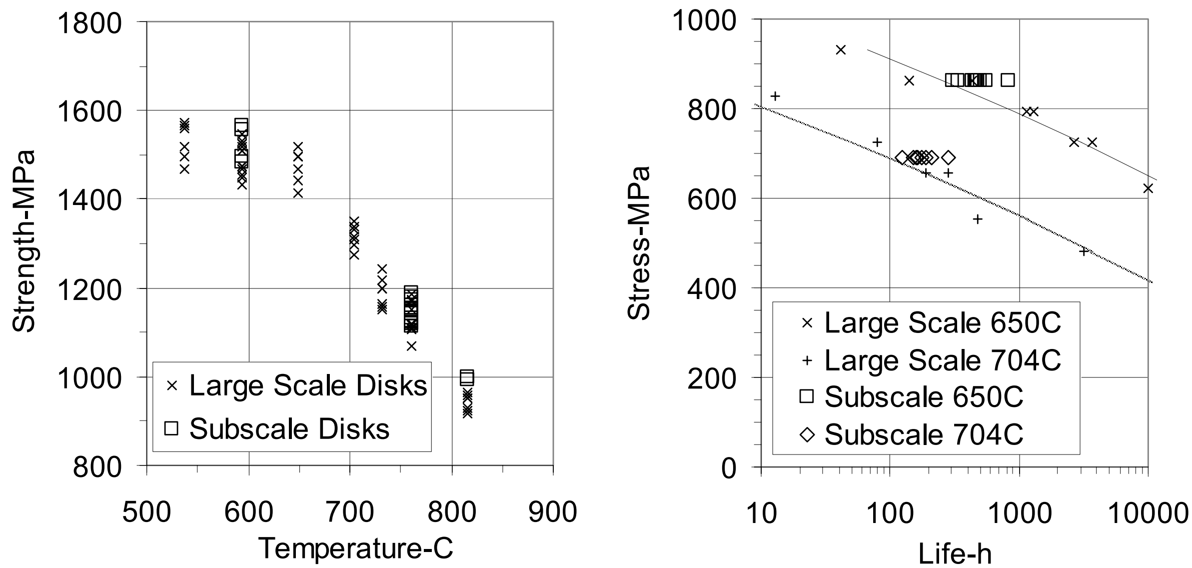
Typical grain microstructures in optical images of etched metallographic sections of specimen grip sections are shown in Fig. 4. These microstructures were from oil quenched and fan cooled supersolvus heat treated disks. Supersolvus material heat treated at about 15 °C above each alloy's solvus temperature had a mean ASTM grain size of 7.1 with a standard deviation of 0.3, and an ALA ASTM grain size of 3.1 with a standard deviation of 0.4 for all alloys. Serrated grain boundaries were usually observed for the slower cooled fan air quenched material, while straighter grain boundaries were observed for the faster cooled oil quenched material. Subsolvus material heat treated at about 25 °C below each alloy's solvus temperature had a mean ASTM grain size of 12 with a standard deviation of 0.2, and an ALA ASTM grain size of 7.4 with a standard deviation of 0.9 for all alloys.

<u>Mechanical Properties</u>

<u>Subscale versus Large Scale Properties</u>. ME3 tensile strengths and creep lives are compared from specimen tests of the subscale disks and large contoured turbine disks over 60 cm in diameter and 10 cm in maximum bore thickness in Fig. 5. The scatter in response observed at each test condition for each disk could be attributed in part to variations in local cooling rate, with higher cooling rates producing higher tensile strength and creep life [1, 5]. The mechanical properties were quite comparable for the two disks, indicating the subscale heat treatments could produce mechanical properties representative of large scale disk material.

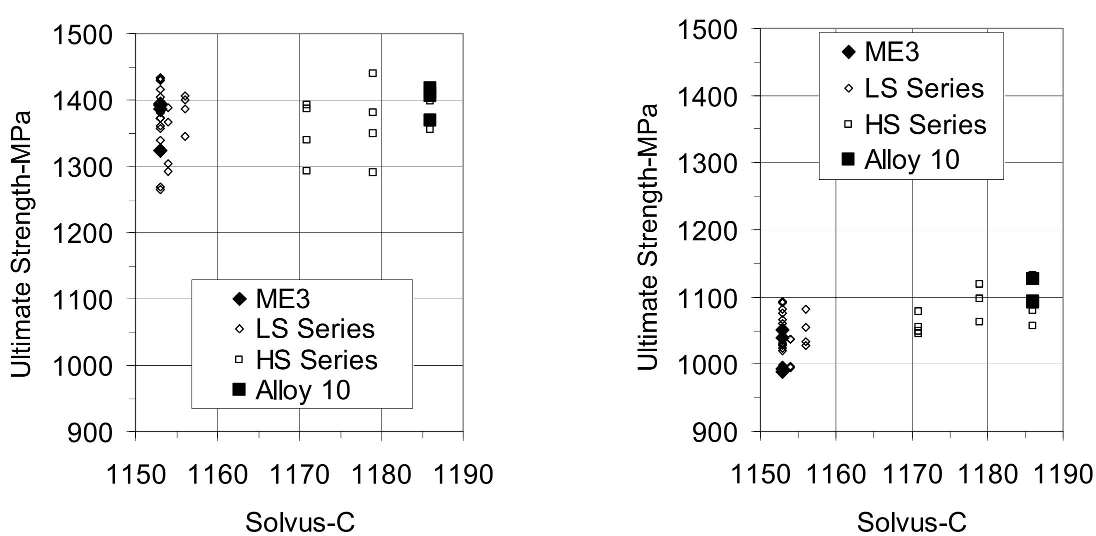
<u>Tensile Response</u>. Ultimate strengths are compared as functions of solvus temperature among all alloys for supersolvus and subsolvus heat treated subscale disks in Figs. 6 and 7. Strength decreased with increasing temperature for both supersolvus and subsolvus heat treated material. Supersolvus material had slightly lower strength than subsolvus material at 704 °C. Alloys with higher solvus temperature had generally higher strengths than the lower solvus alloys. But several lower solvus alloys had strengths approaching the higher solvus alloy levels.

<u>Creep Properties</u>. Times to 0.2 percent creep are compared as functions of solvus temperature among all alloys for supersolvus and subsolvus heat treated subscale as functions of solvus temperature disks in Figs. 8 and 9. Creep response of the coarse grain supersolvus material was superior to that of the fine grain subsolvus material, due to grain size effects. The examined alloys with higher solvus temperature had generally higher creep lives than the lower solvus alloys. But several lower solvus alloys had lives approaching the higher solvus alloy levels.



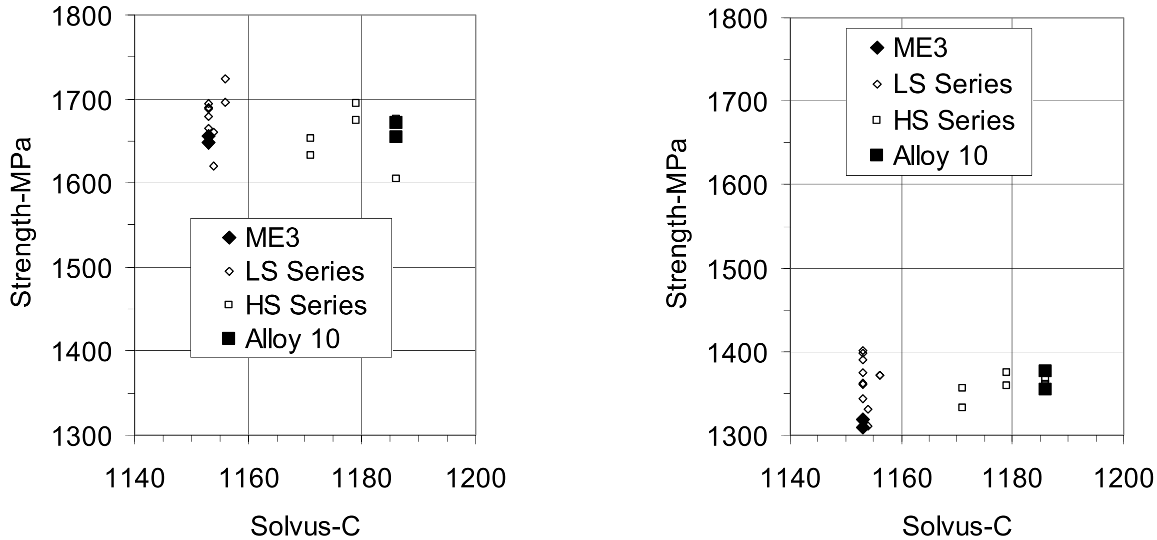
(a) (b)

Figure 5: Supersolvus ME3 subscale versus large scale disk properties: (a) Tensile strength (b) Creep life.



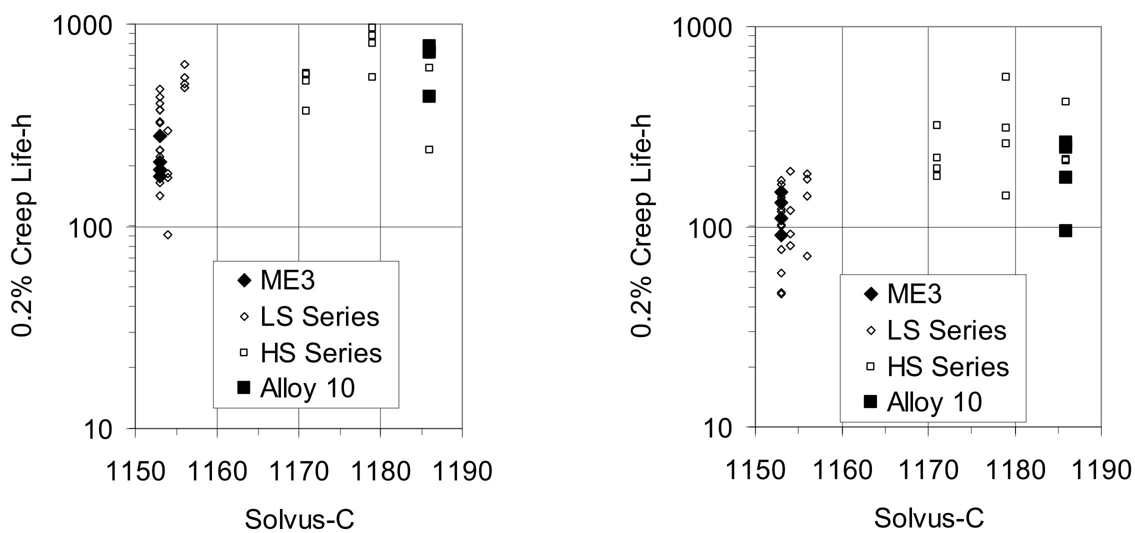
(a) (b)

Figure 6: Supersolvus subscale disk tensile strength for all alloys: (a) 704 °C (b) 815 °C.



(a) (b)

Figure 7: Subsolvus disk tensile strength for all alloys: (a) 538 °C (b) 704 °C.



(a) (b)

Figure 8: Supersolvus disk creep life for all alloys: (a) 704 °C/690 MPa
(b) 815 °C/345 MPa.

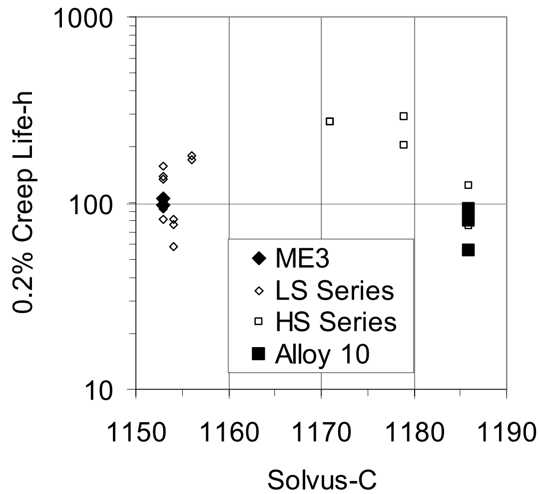


Figure 9: Comparison of subsolvus subscale disk creep life for all alloys at 704 °C/690 MPa.

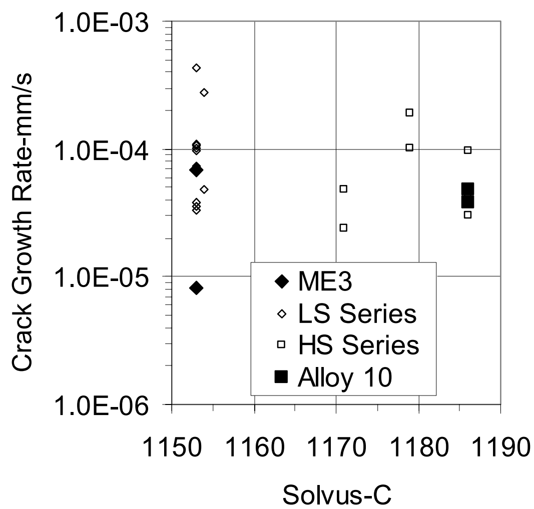
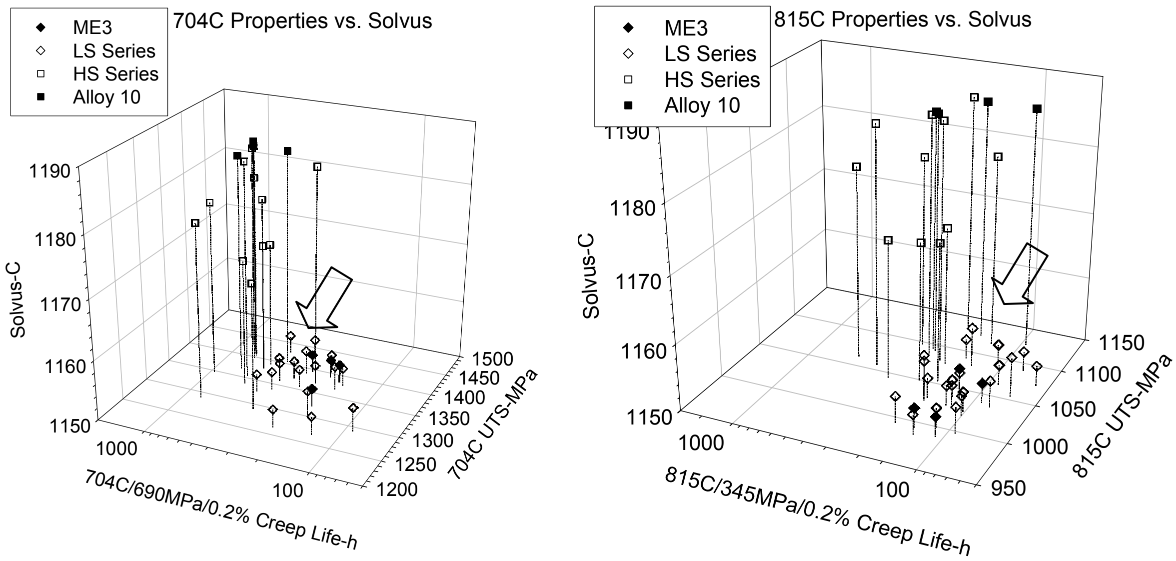


Figure 10: Comparison of supersolvus subscale disk dwell crack growth rates for all alloys at 25 MPa*m$^{0.5}$ in 704 °C/90 s dwell tests.

Fatigue Crack Growth Properties. Dwell crack growth rates at a maximum stress intensity of 25 MPa*m$^{0.5}$ are compared versus solvus temperature among all alloys for supersolvus heat treated subscale disks in Fig. 10. No clear trends were observed with the solvus temperature of the alloy. ME3, Alloy 10, and several LS and HS series alloys had sufficient resistance to dwell crack growth.

Balance of Properties Among All Alloys. Alloys with higher solvus temperature generally had higher strength and creep resistance than the lower solvus alloys. However, the highest strength alloys were more difficult to process and prone to quench cracking, chiefly due to their high solvus temperature. Alloys with lower solvus temperature had generally lower strength and creep resistance, but were less prone to quench cracking. There was no clear trend of crack growth resistance with alloy solvus temperature, strength, or creep resistance. Therefore, the



(a) (b)

Figure 11: Balance of supersolvus tensile, creep, and solvus properties for all alloys: (a) 704 °C (b) 815 °C.

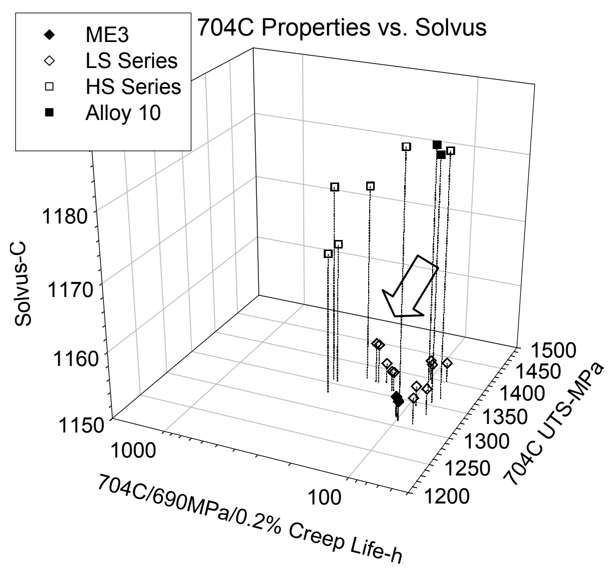


Figure 12: Balance of tensile, creep, and solvus properties for all subsolvus alloys.

most desirable alloy should have high strength and creep resistance combined with low solvus temperature. The balance of strength, creep life, and solvus temperature is compared for the supersolvus and subsolvus heat treated alloys in Figs. 11 and 12. Several LS series alloys did have a favorable balance of improved tensile and creep response combined with low solvus temperature. Among these, an optimal low solvus, high refractory (LSHR) alloy was identified which combined the best attributes of all these alloys, giving exceptional tensile and creep properties at high temperatures with good processing characteristics. The high refractory element levels gave exceptional tensile and creep properties at high temperatures, while the overall chemistry gave good processing characteristics including a low gamma prime solvus and resistance to quench cracking. This LSHR alloy, having a nominal composition in weight percent of 3.5Al-0.03B-0.03C-20.7Co-12.5Cr-2.7Mo-1.5Nb-1.6Ta-3.5Ti-4.3W-0.05Zr-bal. Ni, is now being scaled up for expanded processing and mechanical property assessments.

Summary and Conclusions

A series of subscale experimental powder metallurgy disk alloys were evaluated for their processing characteristics and high temperature mechanical properties. Heat treatment procedures were developed which could reproduce in subscale disks the cooling paths and mechanical properties of large scale disks. Several subscale alloys had superior tensile and creep properties at 704 °C and higher temperatures, but were difficult to process and prone to quench cracking, chiefly due to their high gamma prime solvus temperature. Several other alloys had more favorable processing characteristics due to their lower gamma prime solvus temperature. These alloys often had lower tensile and creep properties at high temperatures. Several experimental low solvus, high property alloys were identified which could build upon the best attributes of all these alloys, giving exceptional tensile and creep properties at high temperatures along with good processing characteristics due to a low gamma prime solvus.

It can be concluded from this evaluation that:

(1) Subscale evaluations of disk alloys can be designed to realistically reproduce the cooling paths and mechanical properties expected from large scale disks.
(2) New disk alloy chemistries can be used to improve mechanical properties at high temperatures.
(3) Alloys having high solvus temperature are more prone to form cracks during quenching.
(4) An alloy can be designed to provide a low solvus temperature for ease in processing with exceptional tensile and creep properties at high temperatures.

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13. ABSTRACT *(Maximum 200 words)*

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